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Considerations on assist gas jet optimization in laser cutting with Direct Diode Laser

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Abstract

The emergence of new generations of laser sources for cutting of metal sheets results in the reopening of research topics that were long closed for established technologies such as CO_2 lasers. After the success of the fiber/disk generation, we now see a third generation of Direct Diode Lasers (DDLs) taking their chance. As the diode laser technology matures and the process boundaries are shifted to meet metal sheet laser cutting requirements, new challenges arise. This paper deals with gas jet optimization in laser cutting with a linearly polarized DDL setup with an output power of 750W. Different concepts were investigated for improving the nitrogen assist gas jet when processing 3 mm thick 304 L stainless steel sheets. After performing a set of tests with conventional conical nozzles, several efforts were made in order to test possible improvements in cutting performance. This included accelerated gas jets designed for an exit Mach number of 2 (both a linearized version of the Laval nozzle and a Minimum length nozzle were tested) and non-axis symmetric nozzle configurations, such as laser to nozzle center offset or nozzles with obround exit shapes. A general discussion on the design methods and procedures for these nozzle shapes is also given. Results of this exercise show the importance of well-designed nozzles for cutting with DDL's and specifically the need to take the beam shape and laser quality constraints into consideration.

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Keywords: nozzle design, laser cutting, diode lasers

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1. Introduction

Most developments in laser cutting of metal sheets in recent years, have been sustained by the increasing availability of greater powers of fiber and disk lasers. As predicted in their early introduction, the performance of these lasers in cutting is finally overcoming CO_2 laser sources. There are still niches were CO_2 is still dominant, mainly due the ten times larger wavelength, but this may as well change with the introduction of better beam shaping capabilities and the constant decreasing of fiber and disk laser investment costs. The diode lasers have come into picture recently, especially after considerable improvements in laser beam quality that have enabled laser cutting applications[1]. These are established technologies in other laser processing fields, but also the main pumping technology used for fiber and disk technologies. Diode lasers are thus potentially the cheapest laser technology, as long as the process requirements are met. There are other advantages that motivate their use, such as efficiency, compactness or maintenance requirements. The possibility of a process specific tailored polarization or wavelength is also an option to consider. Recent research has shown a great potential of polarization control in laser cutting with diode lasers[2]. These developments introduce new variables in the cutting process that must be considered. The different laser material absorption behavior imposed by different polarization strategies, wavelengths or beam geometries are responsible for a different kerf formation. The assist gas flow is intrinsically connected to these changes and needs to be optimized for the new conditions. This opens new research questions in the topic of assist gas jet optimization in laser cutting, especially related with nozzle design. In fact, different nozzle designs have been proposed along the years for laser cutting, such as supersonic[3,4], ring type[5] or auxiliary nozzles[6]. Other authors have focused on explaining important gas dynamic effects, such as flow detachments in the cutting kerf, both experimentally observed and simulate[7].

In this paper the potential of nozzle design for laser cutting with *Direct Diode Laser*s (DDL) will be explored, first through a test campaign with conventional nozzles intended to understand effects and interactions between different laser cutting parameters and afterwards by proposing and testing two concepts for nozzle design improvement.

2. Methods and test experiments with conventional nozzles

2.1. Experimental setup

The experimental setup consisted of a DDL source with maximum output power of 750W mounted on a gantry platform, which allows the control of parameters such as: stand-of-distance, gas pressure and gas type, interchangeable nozzle tips, nozzle to laser alignment, laser power, focal point position and cutting speed. The laser was integrated directly in the cutting head and delivering the beam onto the workpiece focused by a 80 mm focal length lens. With a beam parameter product of 22 mm mrad, a spot size of 350 micron, at a Rayleigh length of 1 mm, can be obtained. The laser was linearly polarized and the experiments were conducted along the direction of polarization. For more information regarding the laser we refer to [2].

The material used for the reported cutting experiments was stainless steel 304 L and the assist gas was Nitrogen.

2.2. Design of experiments

In a first step the experiments were conducted following a full factorial approach for the first four parameters described in Table 1. Two levels were used for each parameter, with exception of gas pressure, where, in an attempt to find a nonlinear (polynomial) effect, four levels were used instead. A total of 32 tests were realized in this exercise. Analysis of data was made with support of a dedicated design of experiments software tool (JMP Pro 12 from SAS). Later, a software option for augmented designs was used in order to include the effect of offsetting the nozzle in relation to the laser beam. A positive offset means the laser beam is closer to the edge of the nozzle in the feed direction. For this new design powers of up to 3rd level and 3rd order interactions were considered, resulting in 18 extra tests. Table 2 presents the parameters for the 50 tests realized along with the measured responses.

For each set of parameters a line was cut where speed was increased in a step-wise fashion, with 50 mm/min increments after each 30 mm of cut length. Starting speed was 900 mm/min. Three different responses were measured in the following order:

Maximum cutting speed: Defined as the highest speed at which full penetration is achieved, independently of the amount of dross, and measured directly on the metal sheet.

Kerf width: Measured on the sheet metal, at the maximum cutting speed length section, it defines the kerf width at the top of the plate (example in Figure 1a).

Average dross height: After sectioning the plate into samples containing the laser cut edges, a picture is taken of each cut cross section for the maximum cutting speeds and later processed using a free photo editing software package (*paint.net*). The background is removed and the total edge surface area evaluated (see example in Figure 1b). The average dross height is calculated as follows:

$$AVG_{dross\ height} = \frac{A_{sec}}{l} - t$$

With A_{sec} the measured section area, t the original material thickness and l the length of the section.

Table 1 - Parameters and levels for experiments with conventional nozzles

Parameter	Symbol	Levels
Focal point depth	F	-1.5; -3.0 mm
Stand-of-distance	SOD	0.5; 1.0 mm
Nozzle inlet pressure	P	10.0; 12.5; 15.0; 17.5 bar
Nozzle exit diameter	D	1.5; 2.0 mm
Offset	O	0.00; 0.25; 0.50 mm

Table 2 - List of parameters and measured responses. Grey highlighted values represent tests with Augmented design

Test number	O	SOD	P	D	F	Maximum cutting speed [mm/min]	Kerf width [mm]	Average dross height [mm]
1	0,00	1,0	12,5	1,5	-1,5	1250	0,43	0,29
2	0,00	1,0	12,5	2,0	-1,5	1250	0,40	0,06
3	0,00	1,0	17,5	1,5	-1,5	1150	0,44	0,23
4	0,00	1,0	17,5	2,0	-1,5	1150	0,39	0,44
5	0,00	1,0	10,0	1,5	-1,5	1300	0,43	0,38
6	0,00	1,0	10,0	2,0	-1,5	1250	0,40	0,45
7	0,00	1,0	15,0	1,5	-1,5	1200	0,44	0,38
8	0,00	1,0	15,0	2,0	-1,5	1200	0,38	0,53
9	0,00	1,0	12,5	1,5	-3,0	950	0,59	0,00
10	0,00	1,0	12,5	2,0	-3,0	1050	0,59	0,02
11	0,00	1,0	17,5	1,5	-3,0	900	0,68	0,20
12	0,00	1,0	17,5	2,0	-3,0	950	0,60	0,11
13	0,00	1,0	10,0	1,5	-3,0	1000	0,62	-0,05
14	0,00	1,0	10,0	2,0	-3,0	1050	0,60	0,02
15	0,00	1,0	15,0	1,5	-3,0	950	0,63	0,02
16	0,00	1,0	15,0	2,0	-3,0	1100	0,57	-0,02
17	0,00	0,5	12,5	1,5	-1,5	1150	0,45	0,17
18	0,00	0,5	12,5	2,0	-1,5	1200	0,41	0,60
19	0,00	0,5	17,5	1,5	-1,5	1350	0,47	0,16
20	0,00	0,5	17,5	2,0	-1,5	1250	0,44	0,26
21	0,00	0,5	10,0	1,5	-1,5	1400	0,43	0,11
22	0,00	0,5	10,0	2,0	-1,5	1250	0,37	0,58
23	0,00	0,5	15,0	1,5	-1,5	1350	0,45	0,30
24	0,00	0,5	15,0	2,0	-1,5	1100	0,36	0,26
25	0,00	0,5	12,5	1,5	-3,0	1050	0,62	0,09
26	0,00	0,5	12,5	2,0	-3,0	1000	0,60	0,07
27	0,00	0,5	17,5	1,5	-3,0	1100	0,68	0,12
28	0,00	0,5	17,5	2,0	-3,0	1100	0,56	0,06
29	0,00	0,5	10,0	1,5	-3,0	1000	0,69	0,10
30	0,00	0,5	10,0	2,0	-3,0	900	0,60	0,08
31	0,00	0,5	15,0	1,5	-3,0	1100	0,60	0,05
32	0,00	0,5	15,0	2,0	-3,0	1100	0,61	0,11
33	0,00	0,8	13,8	1,5	-2,3	1150	0,58	0,10
34	0,25	1,0	10,0	2,0	-2,3	1250	0,49	0,15
35	0,25	0,8	13,8	1,5	-2,3	1150	0,49	0,22
36	0,25	0,8	13,8	2,0	-2,3	1350	0,51	0,27
37	0,50	0,5	13,8	1,5	-1,5	1450	0,38	0,21

38	0,50	1,0	10,0	2,0	-1,5	1200	0,44	0,11
39	0,00	0,8	13,8	2,0	-2,3	1150	0,53	0,09
40	0,50	0,5	10,0	2,0	-2,3	1300	0,47	0,31
41	0,25	1,0	17,5	2,0	-1,5	1500	0,42	0,29
42	0,25	0,5	13,8	1,5	-2,3	1000	0,53	0,21
43	0,50	0,8	17,5	2,0	-1,5	1400	0,36	0,26
44	0,25	0,8	10,0	2,0	-1,5	1350	0,43	0,26
45	0,25	0,8	13,8	2,0	-3,0	1050	0,64	0,14
46	0,25	0,8	17,5	2,0	-2,3	1350	0,48	0,25
47	0,50	0,5	13,8	2,0	-1,5	1350	0,40	0,21
48	0,50	0,5	17,5	2,0	-1,5	1350	0,41	0,23
49	0,50	0,5	13,8	2,5	-1,5	1450	0,43	0,20
50	0,50	0,5	17,5	2,5	-1,5	1500	0,47	0,29

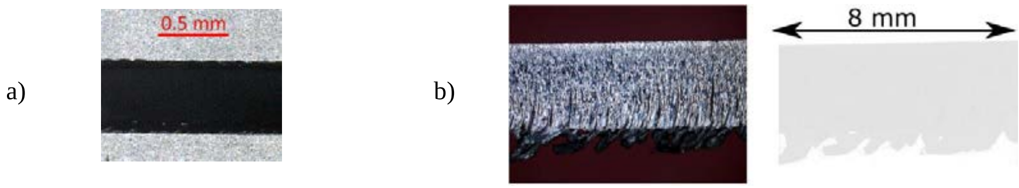


Figure 1 - Example of a microscope picture for a) kerf width measurement and b) dross measurement (original microscope picture on the left and processed section on the right)

2.3. Analysis of cutting results

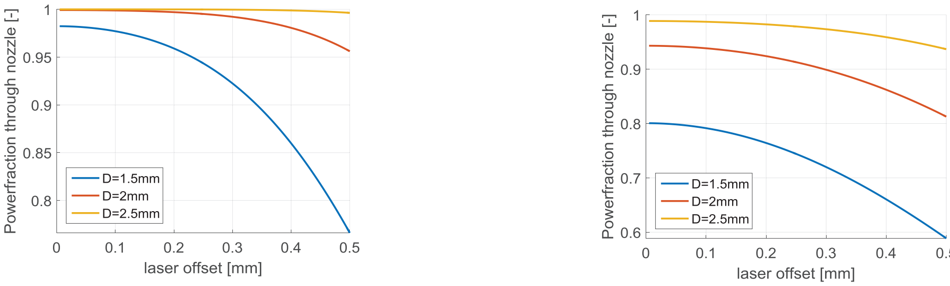
Table 3 gives an overview of the significant effects encountered for the three measured responses, after separately fitting a least squares model to each response. Average dross height has a considerably lower RSquare value which could be related to errors induced by fallen dross before the actual measurement (both during sectioning and handling of the cut samples). The focal point position is clearly the most significant effect for all responses. It is important to notice that, according to the results, a higher focal point position will increase both the maximum cutting speed and the amount of dross while making a smaller kerf width. It is worth mentioning the effect of gas pressure as well, which in contrast to what was initially thought, is not significant for all measured responses, with the exception of a 3rd order interaction (O*SOD*P) for the maximum cutting speed. This could be related with the position of the shock waves in relation to the kerf and, thus, related to the amount of gas flowing into the cutting kerf.

Table 3 – Significant effects listed ($Logworth = -\log_{10}(p\_value)$) for the measured responses. n.s. - stands for non-significant values (at p-value greater than 0.05). + and – signs for main effects indicate a generally positive or negative influence on the response value

	Maximum cutting speed	Kerf Width	Average dross height
Rsquare	0,88	0,93	0,53
F	12,312 (+)	26,349 (-)	6,402 (+)
D*F	4,824	n.s	n.s.
O*F	4,774	n.s	1,890
O	4,607 (+)	n.s	n.s.
O*O	4,334	n.s	n.s.
O*D*F	3,752	n.s	n.s.
O*D	3,279	4,313	n.s.
O*SOD*D	3,165	n.s	n.s.
O*SOD*P	2,817	n.s	n.s.
D	1,607 (+)	4,098 (-)	n.s.

We can see that all main effects and interactions for the parameters F, O and D are significant for the maximum cutting speed, which suggests a possible major process constrain (effects highlighted in grey in Table 3). All three parameters can be responsible for power loss in the nozzle outlet when part of the laser is trimmed by the nozzle. If we consider the integral of a two dimensional Gaussian power density function, corrected for the laser quality and offsets used, we can calculate the expected power loss and obtain the graphs depicted in Figure 2. The power losses can be quite high, which explains, partially, the significance of these effects. Nevertheless, if we look closer to this model, we see that not only the O*O effect is also significant, suggesting a quadratic effect for the offset, but also higher speeds can be obtained at a large offset. We can see this more clearly at the model profile plots depicted in

Figure 3. It is clear that a large offset in combination with a lower F and D will give a minimum speed, as expected from the power loss calculations. In contrast, the peaks of speed are not located at a zero O in combination with higher F and D. In fact, these peaks occur at large offsets for certain combinations of F and D, suggesting a different reason for this positive influence of offset. One explanation could be the increase of overlap area between the nozzle outer gas jet and the cutting kerf for larger offsets. This could lead to a bigger mass flow into the cutting kerf and more momentum being transferred. Another possible reason could be a positive effect of the internal nozzle laser reflections. In this case the reflected light, due to a forward laser offset, is still sent to the cutting kerf, possibly at a more favorable direction with respect to laser material absorption.



a) b)

Figure 2 - Power fraction through nozzle for the two extreme tested conditions, a) SOD=0,5 mm and F=-1,5 mm and b) SOD=1 and F=-3 mm, for different offset and nozzle diameters

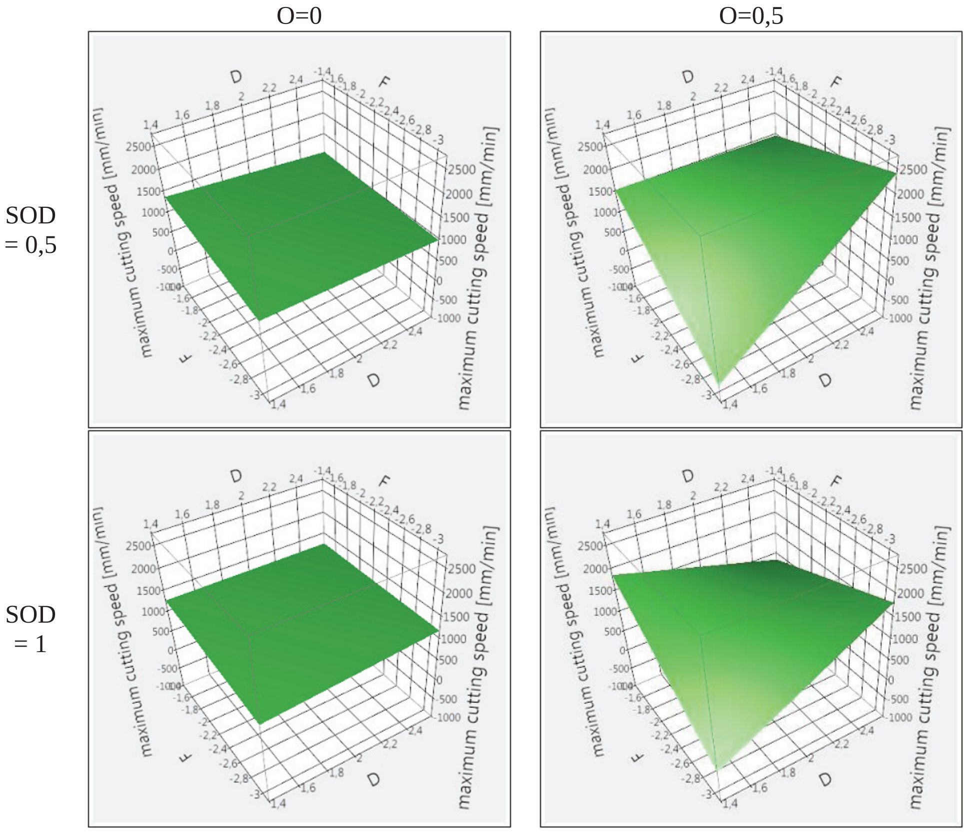


Figure 3 - D and F surface profilers for different O and SOD values help to understand the O*D*F interaction for maximum cutting speed

3. Nozzle design

3.1. Increase gas to melt momentum exchange: The supersonic nozzle

In the benchmarking test results a strong effect of focus position on cutting speed and dross formation could be observed. A focal point positioned in the middle of the sheet offers the highest speed but a poor edge quality. In contrast, if the focal point is positioned at the bottom of the sheet, the lowest amount of dross is obtained. The first investigated idea consist on trying to increase the drag imposed to the melt by the assist gas in order to avoid the formation of dross, even for a higher focal point position.

In laser fusion cutting the viscus drag is a very important factor for the melt expulsion. It is typically proportional to the square of gas speed. The shear stress for internal flows may be a good approximation for the flow inside the kerf and is defined as:

$$\tau_w = \frac{\xi}{8}\rho_g {v_g}^2$$

With ρ_g the gas density, ξ a friction factor generally experimentally determined and v_g the gas speed. It seems reasonable to aim for a nozzle that can accelerate the gas flowing through it. For convergent nozzles the speed will not increase further than Mach 1 with increasing gas pressures, a limit that is easily reached at the usual conditions in laser fusion cutting, and only a well-designed divergent section will increase further the gas speed.

We decided to investigate two types of supersonic nozzles, a convergent-divergent conical nozzle (linear) and a *Minimum Length Nozzle* (MLN), (see [3] for more information about specific nozzle design). These nozzles were designed for a Mach number of 2 at the nozzle exit and with a minimum throat defined by the constrains imposed by the laser beam propagation and the intended focal point position. A sketch of the profiles can be seen in Figure 4.

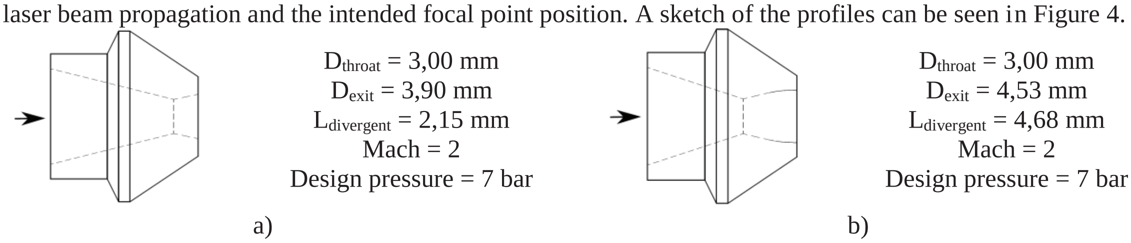


Figure 4 - Designed supersonic nozzles: a) linearized Laval; b) minimum length

The nozzles were manufactured in copper using a micromachining turning setup. In order to evaluate the flow through the nozzles, a double lens schlieren setup was made. From the resulting pictures we can usually evaluate the presence of shocks, since the different shades are connected to density gradients, and thus qualitatively characterise the flow exiting the nozzle. Gas flows for inlet pressures of 7 bar are visible in Figure 5 for both supersonic nozzles and for a standard conical nozzle. On one hand, it seems that the flow exiting the linear convergent-divergent nozzle is highly shocked. This could be explained by assumptions made during the design: a half cone angle of only 12° in combination with high surface roughness may lead to detachment of the boundary layer in the divergent section inside the nozzle, creating this shock pattern. On the other hand, the minimum length nozzle flow is clearly more uniform.

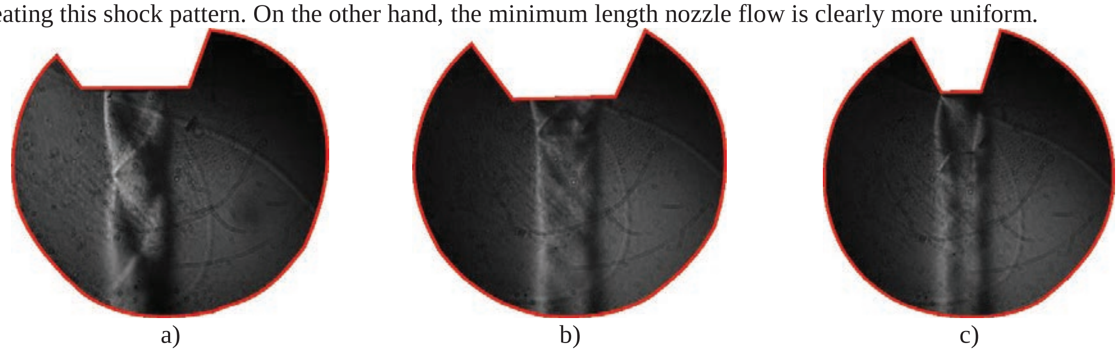
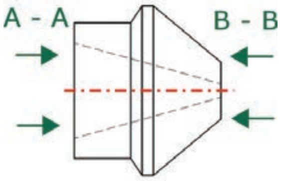


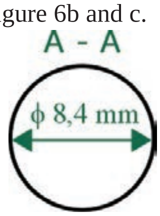
Figure 5 - Flow visualization using a schlieren setup for a) a linearized Laval nozzle, b) a minimum length nozzle and c) a 2,5 mm standard conical nozzle at inlet pressures of 7 bar

3.2. Nozzle to laser offset & gas consumption minimization: The Obround shaped nozzle

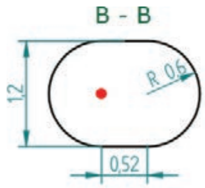
A nozzle that can make use of the offset condition to cut complex shapes may not only be difficult to manufacture but also to steer. It is a fact that, in order to maintain the plane specified by the laser beam axis and the feed velocity as symmetry plane, the axis of rotation to be used in this steering needs to be collinear with the one of the laser. This leads to the need for different manufactural rotation axes for the external and internal nozzle contour. If we take this challenge into consideration the possibility of asymmetric nozzle exit shapes is a given. The overlap of the exit hole, and thus the gas flow shape, can be optimized for a given laser beam and kerf width. In this paper we have created a nozzle that has the same exit area of a standard conical 1,5 mm nozzle but is elongated in the direction of cutting. Since, for the typical ranges of gas pressures used, the gas consumption will be only dependent on pressure, the idea is to increase the overlap without increasing gas consumption. Figure 6 shows a sketch of the designed nozzle with these assumptions in mind. The nozzle was manufactured in copper. The external contour was made by turning in a micromachining setup followed by the drilling of a centered hole of 1mm. The internal profile was finished using wire-EDM, according to the profiles given in Figure 6b and c.



a)



b)



b)

Figure 6 - Detail of obround shaped nozzle: a) nozzle sketch view, b) scaled top view and c) scaled bottom view

4. Cutting results and analysis

4.1. Supersonic nozzle

A total of 4 extra tests were realized with the supersonic nozzles, as depicted in Table 4. It is clear that the target of decreasing attached dross was not achieved. The cutting speed also decreased if we compare it with the best maximum cutting speeds obtained in the benchmarking tests at offset zero and similar SOD and F conditions. The limitations in the minimum throat diameter imposed by the laser beam quality were responsible for a minimum throat of 3 mm and consequently an even bigger exit diameter. On one hand, the cooling effects of the impinging gas on the metal sheet plate may be playing a bigger role than initially expected and be responsible for the lower cutting speed. On the other hand the creation of a strong vortex at the kerf entrance may be blocking the entrance of a uniform accelerated flow into the cutting kerf.

Table 4 - Cutting tests performed with supersonic nozzles show lower speed and no improvement in dross level

Nozzle type	SOD	F	Maximum cutting speed [mm/min]	Kerf width [mm]	Average dross height [mm]
Linear	0,5	-1,5	1050 (-25%)	0,47	0,75
MLN	0,5	-1,5	1150 (-21%)	0,49	0,30
Linear	1,0	-1,5	1050 (-19%)	0,44	0,61
MLN	1,0	-1,5	1100 (-15%)	0,41	0,40

4.2. Obround shaped nozzle

The obround shaped nozzle was tested at the focus point position of -1,5 mm and SOD of 1mm for two levels of pressure, 15 and 17,5 bar. For both cases the cutting speed is higher, 4 and 11% respectfully, when comparing similar conditions with a 1,5 mm standard conical nozzle. This is however accompanied by a significant increase of dross and a decrease of kerf width as can be seen in Table 5.

Table 5 - Cutting experiments with the obround shaped nozzle with comparison with conical nozzle of 1,5 mm at similar conditions

Nozzle type	SOD	P	Maximum cutting speed [mm/min]	Kerf width [mm]	Average dross height [mm]
Obround	0,5	15,0	1400 (+4%)	0,41 (-9%)	0,46 (+53%)
Obround	0,5	17,5	1450 (+11%)	0,36 (-23%)	0,53 (+231%)

5. Conclusions

The benchmarking tests performed with a linearly polarized setup in a 3 mm stainless steel sheet have revealed the complexity associated with laser fusion cutting. The interpretation of effects and interactions between the different parameters on maximum cutting speed, kerf width and average dross shed a light on:

- **Focus position:** highly significant for kerf formation. Highest cutting speeds are achieved in detriment of dross formation at a focal point positioned in the middle of the sheet. A lower focus allows dross free cuts at lower cutting speeds
- **Laser beam quality:** it is a limiting factor for parameters such as offset, nozzle diameter and focal point position due to interaction between the laser and the nozzle tip.
- **Laser to nozzle offset:** A significant improvement in cutting speed was found, even considering the expected high power loss at the nozzle tip.

Two nozzle design concepts were proposed and tested:

- **Supersonic nozzle for increase gas to melt momentum exchange:** Two nozzle designs were tested for a Mach 2 flow. The minimum length nozzle showed the most promising flow pattern in a schlieren setup. Ultimately a lower dross level was not achieved and the cutting speeds decreased. The bigger throat and exit diameter imposed by the laser quality may be responsible for unwanted cooling and turbulent effects.
- **The obround shaped nozzle:** A non-axis symmetric nozzle was designed that is capable of an offset like condition while maintaining similar gas consumption as a standard 1,5 mm diameter nozzle. Improvements in cutting speed of up to 11% were possible but came at the expense of a higher dross level.

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